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Development of Low-rise Over-track Buildings Using Thick Laminate Rubber Seismic Isolation Materials




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Application of seismic isolation technologies to over-track buildings enables a reduction of lower structures accompanying reduced seismic response. That reduction of structures will likely allow cuts in construction time and costs of those buildings that face severe constraints in terms of design and construction. Using seismic isolation to control the area where damage occurs can also enable earlier recovery after a disaster.

There were, however, technical issues faced in achieving seismic isolation of over-track buildings. To overcome those, we came up with a new seismic isolation frame form. Using a model that simulates a low-rise over-track building, we verified safety of the building at earthquakes through trial design and analysis of seismic isolation by the conceived frame form. We were further able to confirm in the analysis that using thick laminate rubber seismic isolation material with vibration reduction performance would improve comfort in the over-track space.

●Keywords: Over-track building, Seismic isolation, Thick laminate rubber, Seismic response analysis

1 Introduction

Unlike with ordinary buildings, over-track buildings face severe constraints in terms of design and construction. Those constraints often lead to increases in construction time and costs, so significant reduction of construction work near tracks is required. Furthermore, in projects involving over-track space development in the greater Tokyo area, reducing vibration caused by running trains is demanded to improve comfort and enable broader use of over-track buildings for applications such as offices and hotels. One of the elements used to meet those needs is seismic isolation technology.

Previous studies demonstrated the possibility of reducing seismic response and thus the number of foundation piles by applying seismic isolation technologies to low-rise over-track buildings. The studies also revealed technical issues as well. This report proposes a new frame form that will overcome the technical issues in achieving seismic isolation of over-track buildings. The report also verifies appropriateness of the form through trial design and analysis study of a model over-track building. We also focus on thick laminate rubber (seismic isolation and vibration control laminate rubber) as seismic isolation material that can also bring about vibration reduction, assessing improvement of comfort by suppressing vibration by trains.

2 Seismic Isolation of Over-track Buildings

2.1 Issues of and Basic Studies in Seismic Isolation

To rationalize the structure of over-track buildings by seismic isolation, locating a seismic isolation layer on the lowest layer as is done with ordinary base-isolated buildings is most effective. That involves the following issues, however.

First, there are spatial constraints in that it is difficult to secure seismic isolation clearance (clearance around a building that absorbs displacement of the seismic isolation layer). Fig. 1 illustrates the concept of seismic isolation clearance. As

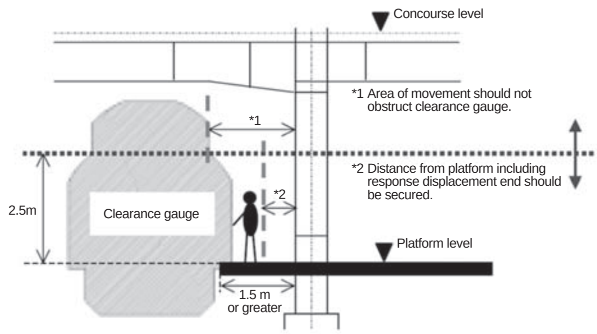

Fig. 1 Concept of Seismic Isolation Clearance

a condition in construction planning, clearance gauge must be secured at the track floor level so as not to disrupt train operation and passenger flow on the platform. When locating the seismic isolation layer at the lowest layer, the dimensions of seismic isolation clearance are restricted to secure that space for trains and passengers.

The second issue is rigidity of the lower seismic isolation structure. Many over-track buildings were designed to have a pile-per-column foundation without underground beams. Therefore, the rigidity of the lower seismic isolation structure is smaller than that of ordinary base-isolated buildings. Such rigidity could cause large rotational deformation of the seismic isolation layer, leading to concerns about a decrease in the kinetic properties of the seismic isolation thick laminate rubber.

The third issue is the space where dampers—members for attenuation—are to be installed. Usually, the height of the first floor of the over-track building (track level) is larger than other floors in order to secure clearance gauge. Making that height as small as possible is important for effective use of the over-track space. In projects involving building expansion or requiring harmonization of planning with nearby buildings, the seismic isolation layer needs to be constructed without changing the floor level of existing or nearby buildings. From a viewpoint of smaller a footprint, dampers that are incorporated to the supports are more appropriate. But, when such dampers cannot cover

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the damping volume required to control the deformation of the building at an earthquake, additional space for the dampers is necessary. We thus need to develop a new frame form to carry out rational construction planning by seismic isolation in spaces with such constraints.

2.2 Proposal of a New Frame Form

In order to select the optimal frame form for seismic isolation of over-track buildings, we studied four frame plans as shown in Table 1 that have different locations for the seismic isolation layer. That study was done through static analysis where the seismic isolation layer was displaced horizontally by approx. 30 cm. For rigidity of the seismic isolation layer, we used equivalent rigidity by a hysteresis damper that corresponds to a support member (seismic isolation and vibration control laminate rubber).

Table 1 shows the analysis results. With pile head seismic isolation, the rotation angle that occurred on the seismic isolation layer exceeded 1/50 while the pile head displacement was the smallest and the design stress of the pile was most reduced. With second floor column base seismic isolation and vibration control (not including the load of the second floor), the area of seismic isolation was limited. For that reason, the seismic isolation effect was smaller, pile head displacement was largest and deformation angle between layers of the track floor was too large at 1/30. In contrast, with second floor column base seismic isolation and vibration control (including the load of the second floor), both the pile head displacement and the rotational deformation were controlled. Furthermore, in this plan, seismic isolation clearance is easily secured since the seismic isolation layer is located above the track floor. This plan can thus overcome the aforementioned first and second issues. We therefore decided to study this frame form.

To overcome the third issue, we developed the new frame form shown in Fig. 2. To minimize the height of the seismic isolation layer, we bended the lower beam of the seismic isolation layer in the direction perpendicular to the track where beam depth is particularly restricted and placed it and two upper beams in a position where those did not horizontally interfere to each other. That brought about reduction of height while securing damper space. In the direction parallel to the track, too, we applied two upper beams of the seismic isolation layer taking into account reduction of beam depth and setting of a jack when replacing the frame components.

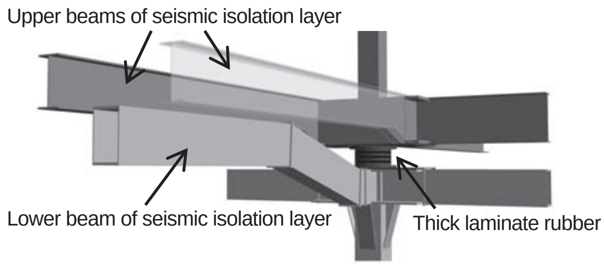
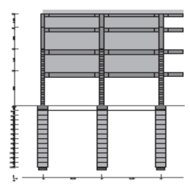
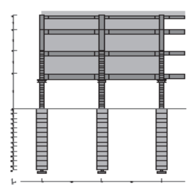
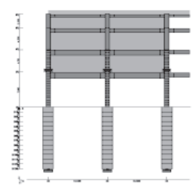
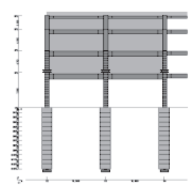


Fig. 2 Frame Form Around Seismic Isolation Layer

Table 1 Static Analysis Results at 30 cm Displacement of Seismic Isolation Layer by Horizontal Force

	Pile head seismic isolation and vibration control proposal		First floor column capital seismic isolation and vibration control proposal		Second floor column base seismic isolation and vibration control proposal (including second floor load)		Second floor column base seismic isolation and vibration control proposal (not including second floor load)	
								
Max. displacement of seismic isolation layer δ (cm)	33.4		32.3		31.3		32.7	
Max. displacement of pile head δ (cm)	3.8		8.5		8.2		21	
Max. deformation angle of track level (rad)	1/63		1/43 (First floor to beneath seismic isolation layer)		1/83		1/30	
Max. deformation angle between third and upper floors (rad)	1/159		1/298		1/286		1/203	
Rotational angle of upper and lower members of seismic isolation layer (rad)	Pile head	First floor column base	First floor column capital	Third floor column base	First floor column capital	Third floor column base	First floor column capital	Third floor column base
	1/225	1/36	1/46	1/232	1/225	1/144	1/66	1/104
Max. inclination angle at seismic isolation layer (rad)	1/36		1/46		1/144		1/66	
Rotational angle at seismic isolation layer (rad)	1/43		1/57		1/400		1/181	

3 Trial Design and Analysis Study of Seismic Isolation

3.1 Design Standard

Table 2 shows the target performance of seismic isolation design. The design input of seismic motion for the study conforms to the spectrum of "extremely rare level of seismic motion in construction" ("Architecture L2") specified in Announcement No. 1461 of the Ministry of Construction Official Gazette (Supplement No. 106)[1]. Input that conforms to "level 2 seismic motion spectrum II" ("Railway L2") is specified in the Design Standards for Railway Structures and Commentary (Seismic Design)[2]. Such seismic motion is equivalent to that of the required horizontal bearing capacity and the maximum level earthquake in the Structural Design Standards for Structures (Low Level) Above Tracks[3]. With Railway L2, limit in rotational deformation along with limit in contact pressure are defined as target performance of the seismic isolation laminate rubber. Further targets are one-rank improvement of the vibration performance evaluation of concourse floor in relation to railway vibration by reducing vibration using seismic isolation and vibration control laminate rubber as well as one-rank improvement of the applicable grade for solid-borne sound.

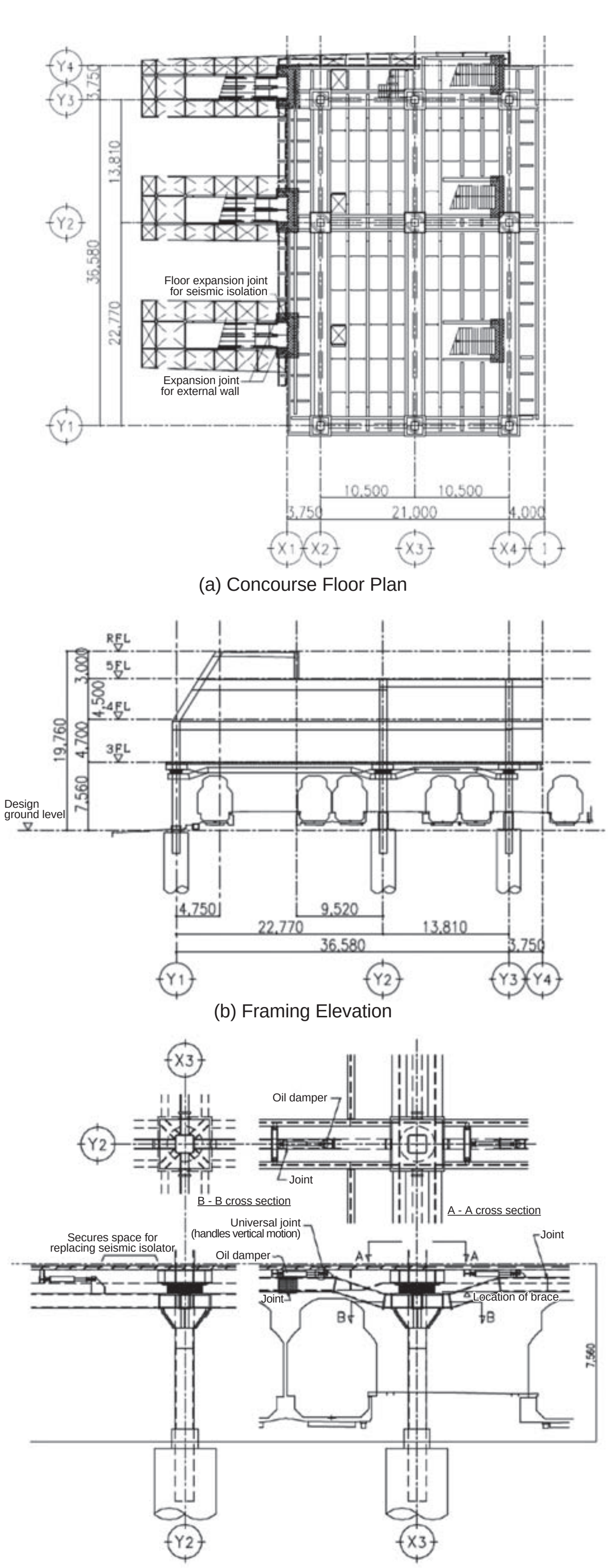
3.2 Trial Design of Seismic Isolation

To study details of the case where the proposed seismic isolation frame is applied to an actual building, we made trial design of seismic isolation for a low-rise over-track building with all underground beams omitted. The upper structure of the building was pure steel rigid frame structure filled with concrete in the columns on the track level to secure rigidity. The placement of columns limits the maximum span in the direction perpendicular to the track to approx. 23 m. On the track level, the clearance gauge and the distance from the platform end limit the column diameter. For the beams just above the track level, clearance gauge particularly in the direction perpendicular to the track needs to be considered, and that constrains beam depth. The foundation is planned as cast-in-place concrete piles. Vertical support is necessary as well as control of horizontal deformation and securing of bearing capacity in times of earthquake, so the columns have to be large in diameter.

To overcome the issues in seismic isolation of over-track buildings, we applied second floor column base seismic isolation where the seismic isolation layer is placed directly above the track floor and adopted a frame with lower beams bended in a direction perpendicular to the track, as shown in Fig. 3. The laminate rubber used is 1,500 mm in diameter at the center of the building and 1,100 mm in diameter at the end of the building. We further placed U-shape dampers (NSUD45) to add attenuation and control deformation by wind load. To secure damping volume, total seven oil dampers were installed.

Table 2 Target Performance (Criteria)

External force			Level 2 (extremely rare level of seismic motion)	Railway L2
Upper structure		Between-floor deformation angle (skewered model, center of gravity)	Less than 1/200	—
		Stress level of column, beam and quake-resistant wall members	1) Bending and axial stress level less than short-term permissible stress level 2) QL+1.0 QE2 less than short-term permissible stress level *Considering additional cross-section force by vertical seismic motion	
		Acceleration on floors higher than seismic isolation layer (excluding RF)	Less than approx. 200 cm/s^2	
Seismic isolation layer	Laminate rubber	Horizontal displacement	Less than 300 mm (250% strain)	Less than 550 mm (400% strain)
		Tension contact pressure	Tension strain less than 0.5% Less than 0.5 N/mm^2	Tension strain less than 0.5% Less than 0.5 N/mm^2
		Compression contact pressure	Compression limit strength in relation to laminate rubber strain less than σ cr × 0.9	Compression limit strength in relation to laminate rubber strain less than σ cr
		Rotational deformation	—	1/50
	Oil damper (displacement, reaction force)		Less than limit displacement (500 mm) Less than max. bearing force (313 kN)	Less than limit displacement (500 mm) Less than max. bearing force (313 kN)
Lower structure		Between-floor deformation angle (skewered model, center of gravity)	Less than 1/150 (excluding rotational element by pile deformation)	Response deformation less than retention deformation
		Stress level of column, beam and quake-resistant wall members	1) Bending and axial stress level less than short-term permissible stress level 2) QL+1.0 QE2 less than short-term permissible stress level *Considering additional cross-section force by vertical seismic motion	



(a) Concourse Floor Plan

(b) Framing Elevation

(c) Details of Seismic Isolation Layer Mounting

Fig. 3 Building Overview

3.3 Seismic Response Analysis Using the 3D Frame Model

The analysis model was a 3D frame model that took into account the bend of the lower beams of the seismic isolation layer, and the model had rigid floors above the isolation layer and non-rigid floors under the isolation layer. It was difficult to evaluate the ground and pile foundation as support springs as was done with the SR model because the frame form was without footing beams. Thus, we applied a mass system model that unified the ground, foundation and upper structure and input seismic motion in ground springs as single input (Fig. 4).

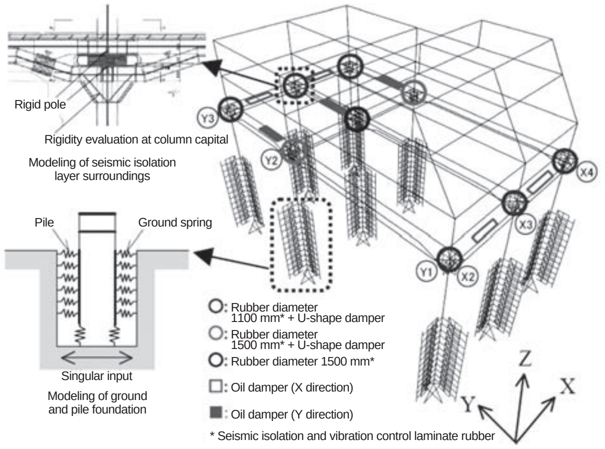


Fig. 4 Overview of Analysis Model

We set and used a total of four engineering foundation waves for the design input seismic motion. Those were three waves of the Architecture L2 (Hachinohe NS phase, Kobe NS phase and uniform random number phase) and a Railway L2 wave (amplification characteristic of the surface ground examined in the implemented design). The structural attenuation given in proportion to the strain energy was 2% for the on-ground building frame, 3% for the piles and 5% with the Architecture L2 and 10% with the Railway L2 for the ground springs. For seismic isolation material, it was 0%.

Fig. 5 shows the maximum response values of acceleration, story sheer force and displacement. The acceleration values of the lower structure were large because vibration was roughly separated between the upper and lower structures. The maximum response value of the upper structure, excluding RF with the Architecture L2, was 259 gal. That was a little larger than 200 gal, the target value, because we planned to provide a stiffer seismic isolation layer to prevent excessive deformation of the layer even with the Railway L2 (approx. 30 cm with the Railway L2). Story sheer force values were smaller than the elastic limit strength at every floor in every case. With Architecture L2, it was lower than the story sheer force for short-term design (C_1 = 0.2, Ai distribution). The deformation of the seismic isolation layer also met target performance in all cases. We were therefore able to confirm the effect of seismic isolation in reduction of seismic force.

Fig. 6 shows the relationship between contact pressures and sheer strain with the seismic isolation and vibration control laminate rubber where +/-0.5 G is added according to the vertical motion response. As shown, both the maximum and minimum values were within the permissible contact pressure. The maximum rotational angles acting on the vibration control laminate rubber, for which we were concerned because there were no footing beams, were 1/297 with the Architecture L2 and 1/197 with the Railway L2, proving that there was no impact. Based on these results, we determined that the seismic isolation and vibration control laminate rubber could secure sufficient seismic isolation performance in the study model.

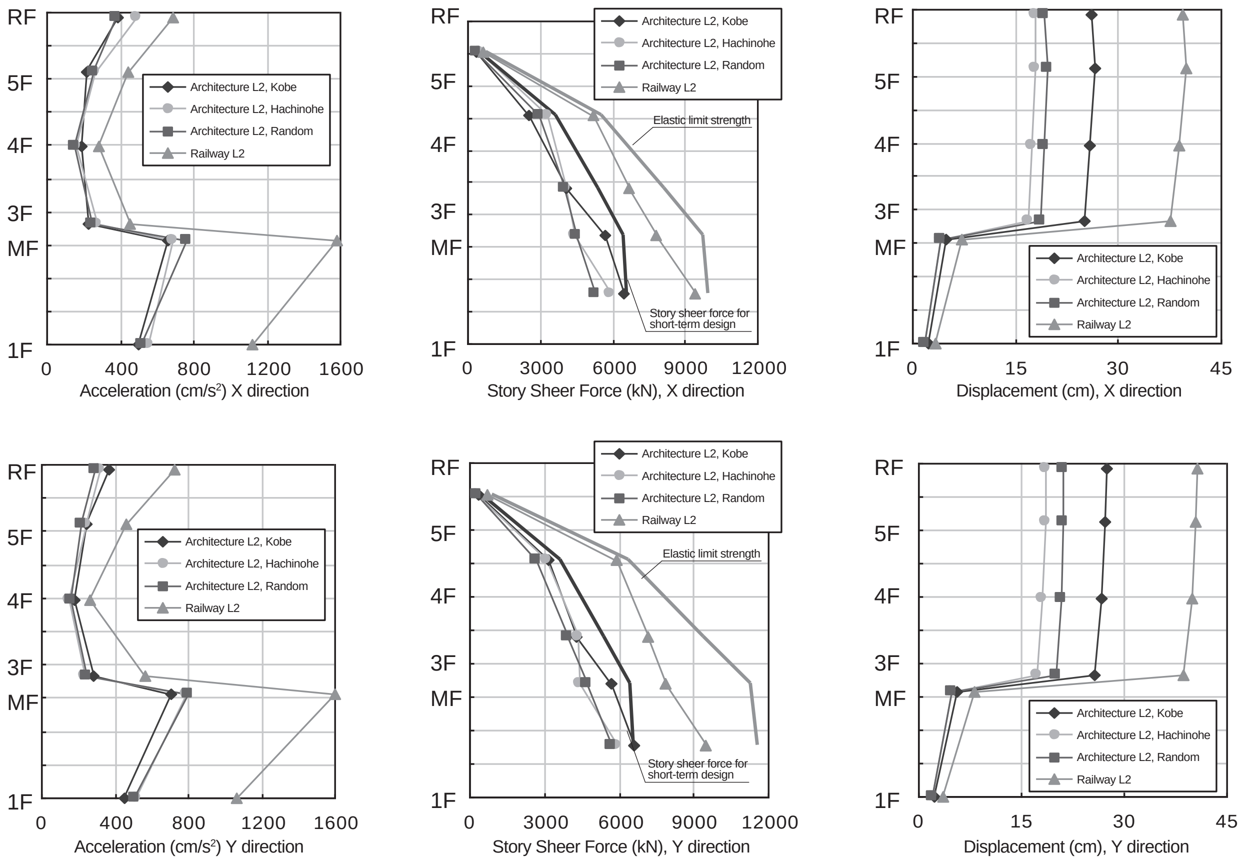


Fig. 5 Maximum Response Values

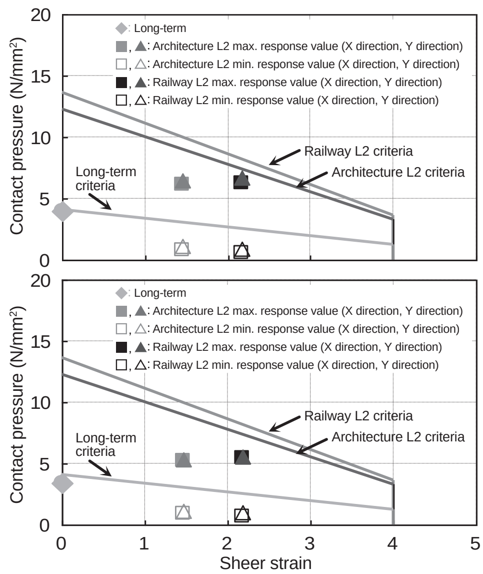


Fig. 6 Relationship between Contact Pressure and Sheer Strain (upper: 1100 mm diameter, lower: 1500 mm diameter)

4 Study on Vibration Control Performance

4.1 Overview of Study on Vibration Control Performance

We verify the vibration control performance of the over-track building using seismic isolation and vibration control laminate rubber as well as verify solid-borne sound in an office assumed to be in the building.

For verification, we analyzed an over-track building where trial design for seismic isolation was done. That analysis was made using a earthquake resistance model, a seismic isolation model (using seismic isolation laminate rubber as the seismic isolation member) and a seismic isolation and vibration control model (using seismic isolation and vibration control laminate rubber as the seismic isolation member) as shown in Fig. 7, and we compare the results of those.

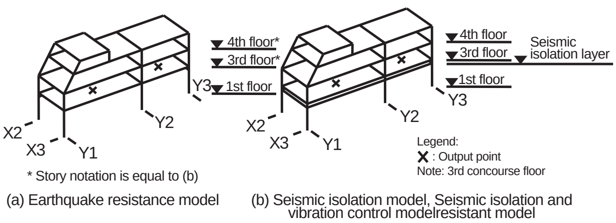


Fig. 7 Analysis Model

We measured the vibration at the first floor column base of an over-track building while trains passed and used that vibration as the input value of the railway vibration in the analysis. Measurement was done at passing of individual trains, and data of nine trains of the same series was averaged. Fig. 8 shows the vibration acceleration level of the measurement results. Simultaneously inputting the measurement results to all six of the first floor column bases in each of the earthquake resistance, seismic isolation and seismic isolation and vibration control models, we calculated the predicted vibration of each model in regard to railway vibration by analyzing the frequency responses. Based on the predicted vibration, we attempted to evaluate the vibration control performance and the solid-borne sound when applying the seismic isolation and vibration control frame structures to check whether the target values in sections 2 and 3 could be met.

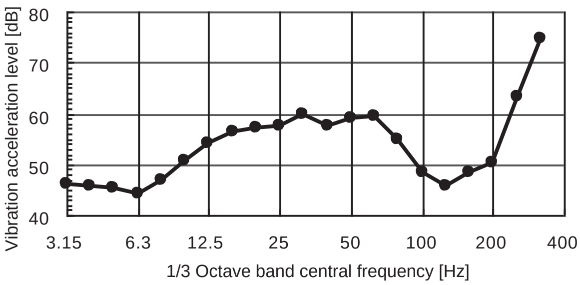


Fig. 8 Input Value (1st floor column base)

4.2 Method and Results of Predicting Response to Railway Vibration

The response with each model was predicted as follows.

1) Analyze the frequency response by giving the first floor column base unit acceleration of a fixed frequency domain, and calculate the amplification at each output point (marked "x" in Fig. 7) to the standard point (first floor column base).
2) Multiply the amplification by the input value shown in Fig. 8, and calculate the predicted response without consideration of background vibration.
3) Using the background vibration measured when no trains are running, calculate the predicted response adjusted with elements other than train vibration.

Fig. 9 shows the results of floor response predictions.

Looking at the whole area of frequency domain, we found no large differences between the earthquake resistance model and the seismic isolation model, although vibration was reduced slightly with the latter model. That result could be predicted because the vertical rigidity of usual seismic isolation laminate rubber was almost the same as that of the earthquake resistance model. With the seismic isolation and vibration control models, the vibration acceleration level was reduced compared to other two models. In the frequency domain between 63 Hz and 125 Hz too, which is characteristic of railway vibration, the reduction effect was demonstrated.

4.3 Evaluation of Floor Vibration Environment in Regard to Railway Vibration

As we focused on the effect that differences of support conditions of the upper structure have on the vibration characteristics in this study, we intentionally did not model the apparent span reduction effect of the double girder of upper beams of the seismic isolation layer. Thus, analysis of the natural frequencies of each frame form showed that the primary natural frequencies of the Y1–Y2 floor and the Y2–Y3 floor were approx. 4 Hz and approx. 8Hz. In regard to railway vibration, the Y2–Y3 floor is relatively largely affected. Particularly with the seismic isolation and vibration control model, the natural frequencies of the upper and lower structures were approx. 10 Hz or less, leading to concern about the impact on the floors. For the Y1–Y2 floor, on the other hand, we have to pay attention to the impact of

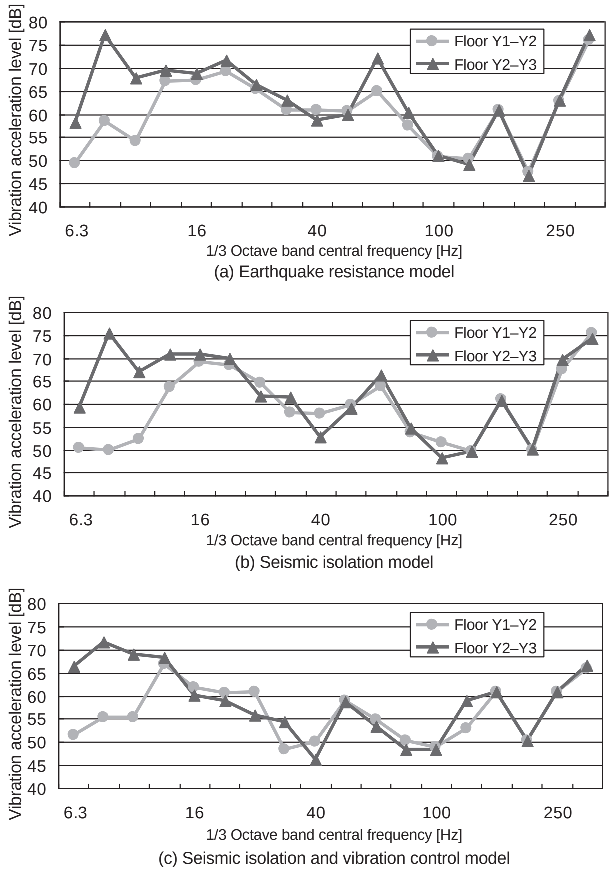


Fig. 9 Response Prediction Results

walking vibration by crowds, even though the input of railway vibration is small. Such total floor performance evaluation will be carried out in more detailed discussion at a later stage of more specific research. Here we evaluate the floor performance in regard to railway vibration using a value larger than 6.3 Hz obtained in the response prediction.

As an example of the study of individual models, the performance curves of the third and fourth floor of the seismic isolation and vibration control model are shown in Fig. 10. Table 3 shows performance evaluation of the Y1–Y3 floor and Y2–Y3 floor of each model[4].

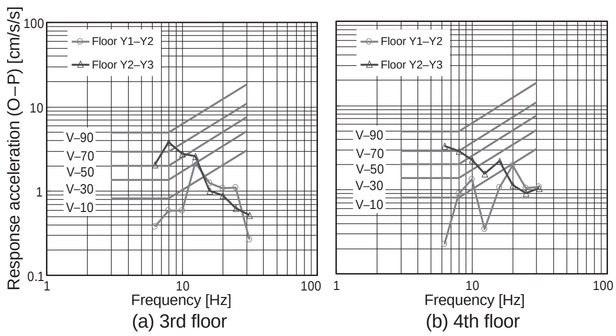


Fig. 10 Floor Performance Curves of Seismic Isolation and Vibration Control Model

Table 3 Floor Performance in Relation to Railway Vibration

Floor position		Earthquake resistance model	Seismic isolation model	Seismic isolation and vibration control model
Y1–Y2	4th floor	V–50	V–50	V–10
	3rd floor	V–30	V–30	V–30
Y2–Y3	4th floor	V–70	V–70	V–70
	3rd floor	V–90	V–90	V–70

Compared to the earthquake resistance model, the seismic isolation model showed a tendency for slight vibration reduction. However, it could not achieve an increase in performance rank. In contrast, the seismic isolation and vibration control model demonstrated vibration reduction effect in total. Despite the tendency for vibration reduction, performance of that model remained at the same rank as other models at the fourth floor Y2–Y3 floor because amplification in the design frequency domain was found in the seismic isolation and vibration control layer. With this model, performance was improved by one rank for the third floor Y2–Y3 floor of the concourse floor and by two ranks for the fourth floor Y1–Y2 floor.

4.4 Analysis and Study of Solid-borne Sound in Regard to Railway Vibration

We analyzed solid-borne sound in the following conditions.

- Office of L22 m × W5 m × H2.7 m assumed between the third floor X2X3–Y1Y2 floors.
- Office interior finishing with…
  Floor: Glass fiber reinforced concrete (GRC) free access floor + carpet tiles
  Ceiling: Particle board (PB) sub-ceiling + rock wool acoustic panel
  Walls: All-surface window (X2 side), PB (other walls)

We adopted the high vibration acceleration level prediction results on the center of the floor between Y1 and Y2. And we set the predicted value of -7 dB at 250 Hz as the vibration acceleration level for the vibration acceleration level at 500 Hz according to the building frame vibration data gained in past studies[5]. It was assumed that the vibration of the third floor between Y1 and Y2 would be uniformly transmitted to the floor, walls and windows of the third floor and the vibration of the fourth floor between Y1 and Y2 transmitted to the ceiling.

As the prediction formula of solid-borne sound, the following formula taking into account the vibration amplification and acoustic radiation efficiency of the interior material in geometrical acoustic theory was applied.

$$SPLs = La + \Delta la + 10\log(S/A) - 20\log10f + 10\log10\sigma + 36$$

$SPLs$: In-room acoustic pressure level by solid-borne acoustic radiation from each interior part [dB]
σ: Radiation coefficient
La: Vibration acceleration level prediction result at center of floor frame [dB]
Δla: Vibration amplification of each interior part [dB]
f: Frequency [Hz]
S: Area of each interior part [m^2]
A: In-room sound absorption [m^2]

Fig. 11 shows the prediction results of the solid-borne sound in the presumed office. We confirmed that the solid-borne sound was significantly reduced with the seismic isolation and vibration control model in frequencies other than 125 Hz compared to results with the earthquake resistance model and the seismic isolation model. The applicable grade[5] would be about Grade 2 with the seismic isolation and vibration control model in an open office.

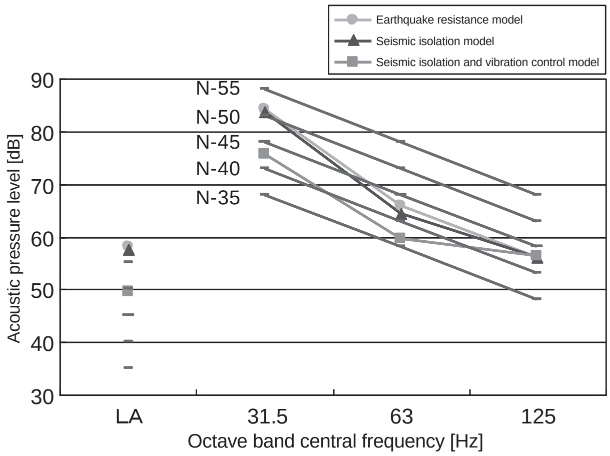


Fig. 11 Prediction Results for Solid-borne Sound

5 Conclusion

We considered a new frame form that was appropriate for seismic isolation of over-track buildings and conducted trial design for a low-rise over-track building as the model.

The analysis results of the seismic response of the studied model confirmed that, for the most part, targets of performance to secure safety of a building in case of earthquake could be met.

The analysis and review also confirmed that using thick laminate rubber as the seismic isolation member would bring about effects in vibration and sound control in terms of railway vibration, leading to the improvement of the comfort of the over-track building.

Reference:

1) Ministry of Construction Announcement No. 1461, Official Gazette (Supplement No. 106) [in Japanese] (May 30, 2000)
2) Railway Technical Research Institute (RTRI), Design Standards For Railway Structures and Commentary (Seismic Design) [in Japanese] (October 1999)
3) RTRI edit., *Sennro Joku Kenchikubutsu (Teiso) Kozo Sekkei Kijun* [in Japanese] (June 2009)
4) Architectural Institute of Japan, *Guidelines for the evaluation of habitability to building vibration* [in Japanese]
5) Architectural Institute of Japan, *Kenchikubutsu no Shaon Seinou Kijun to Sekkei Shishin* [in Japanese]